

A Comparative Characterization of Smart Textile Pressure Sensors

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Abstract—This research study investigates the impact of various insulating textile materials on the performance of smart textile pressure sensors made of conductive threads and piezo resistive material. We designed four sets of identical textile-based pressure sensors each of them integrating a different insulating textile substrate material. Each of these sensors underwent a series of tests that linearly increased and decreased a uniform pressure perpendicular to the surface of the sensors. The controlled change of the integration layer altered the characteristics of the pressure sensors including both the sensitivity and pressure ranges. Our experiments highlighted that the manufacturing design technique of textile material has a significant impact on the sensor; with evidence of reproducibility values directly relating to fabric dimensional stability and elasticity.

Keywords— Smart textiles, pressure sensors, wearable technology, e-textiles, integrating fabric

I. INTRODUCTION

The term "Smart Textiles" pertains to the usability of common fabrics beyond simply wearing them and expand into the ability to interact with either a wearer or their environment. When non-textile electronics are directly added to the garment the term "e-textiles" joins the scope [1],[2]. In recent years, wearable e-textile technology has witnessed a transition from research to commercialization. Companies like Clothing+, Interactive-wear, and Sefar AG have recently launched e-textile based products into the market [1]. In an effort to transform ordinary garments into wearable connected devices; textile sensors which are lightweight, thin and compatible with the users lifestyle have gained popularity [3]. Smart textile sensors including flexible temperature sensors, strain gauge sensors, electromagnetic induced sensors, and pressure sensors have been studied and explored in various ways [4].

As our expertise within the topic of material science continues to expand, the opportunity for the exploitation of interdisciplinary collaboration with people specialized in this field textile for medical applications of textile sensors continues to become more lucrative. Not only are these sensors inconspicuous - allowing for the capture of patient data less biased by a clinical setting than ever before - they allow for another facet to the human-centered health-care platform sought out by many professionals. This will allow the user to become aware of their personal health; a method of facilitating the responsibility of each user to their personal well-being [5].

The customization of e-textiles begins in minute details; the very fibers of textile could be flexible, conductive, durable yarn processed to contain arrays of organic light emitting diodes (OLEDs) as presented at Harvard University by [6]; impregnated with both highly conductive and popular nanocarbon filaments to ensure conduction [5],[7]-[8], or there's the path of creation of polymerized

poly(3,4-ethylene dioxythiophene) (PEDOT)-coated bers [7]. These miniature methods point to seamless comfortable patient monitoring.

An alteration more visible to the naked eye is the decision of which conductive materials are integrated within nonconductive isolating materials and the method of integration. This includes, and is not limited to, adhesive conductive elastomers (CE) with the ability to adhere to Kinesio Tape for piezoresistive strain sensors [9], capacitive sensors with conductive ink printed to interface alternating flexible and rigid materials, or even CAD Embroidery of conductive filaments [10]. Another fascinating iteration is natural and synthetic piezoelectric wearable sensors. A reversible converter between charge and mechanical stress able to self-generate electricity [11].

Maintaining a comfortable unobtrusive design is one of the key aspects of integrating wearables into societal daily lifestyles. If this device is obtrusive or uncomfortable, no matter the size, it skews results due to increased pressure or patient irritation upon contact [12]. As said in [8], A means of seamless integration is required to develop true textile sensors. The exploitation of standard nonconducting fabric that people already have an affinity to wear as isolating material would heighten the adaptation of wearable electronics into a ubiquitous aspect of everyday lifestyle.

II. SENSORS

A. Design

The smart textile-based pressure sensor used on this work consists of three layers. Fig. 1 shows how the individual layers of the sensor design along with the contained circuit design that creates a 2-centimeter by 2-centimeter pressure sensing matrix enforced by Velostat. The material layers acting as parallel plates, as well as the variable exploited within this experiment, are the integrating fabrics. Velostat is typically used to protect components sensitive to electrostatic discharge, and its properties are generally not affected by age or humidity [13]. The Velostat is our sensing region; it has a thickness of 0.1 millimeters, a volume resistivity of 500 ohm-centimeter and surface resistivity of 31,000 ohms per centimeter squared.

Each sensing region operates independently and all four undergo minimal cross-talk while they contribute an analog output signal. The circuit has been hand sewn to ensure both consistent contacts between Velostat and conductive thread, in conjunction with a consistent cross-over location of the conductive threading. The combination of textile layers and Velostat creates a measurable piezoresistive effect that linearly translates the applied pressure placed onto the sensor into an output resistance [1]. The increase resistance output in correlation to the voltage applied can be attributed to Ohms Law (1). Where V refers to the applied voltage, while I and R refer to the current flowing through the circuit and resistance of the material respectively.

$$V = IR \quad (1)$$

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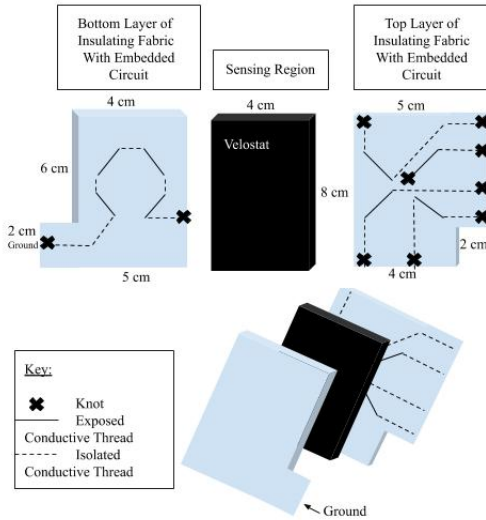


Fig. 1. Above is a view of the piezo resistive circuit diagram separated into three layers. In the bottom row you'll see a simplified version of this circuit in the fashion that you would stack the three layers. Please note that the bottom layer has the exposed conductive thread in contact with the Velostat and has been flipped in the z-direction so the circuit diagram is hidden.

The advantage of piezoresistive materials we are capitalizing upon is the fabrication with flexible materials, as well as the idea that they are robust against noise [14]. The choice of the 2-centimeter by 2-centimeter pressure sensor matrix is based on ease of replication and a connection complexity at par with existing products.

B. Materials

Integration fabric is generally used as insulation between connections; although, there are other prevalent properties of the integrating layer that could affect a fabric-based sensor. Some examples are the appropriate manufacturing techniques allowing induced the stretch and material deformation applicable to each application. Along with the various electrical properties of the materials used, and how these properties interact with each other [15]. The examples of elasticity and resilience have been ignored for this study. This work reports on the effect various properties inherent within an integration layer enact on the sensing abilities of a geometrically basic 2-centimeter by 2-centimeter Velostat [13],[16] based pressure sensing matrix. We will then compare how sensor usability is altered by an integration materials fabrication technique such as weaving, knitting, printing, or couching [5],[11],[10].

The integration layers involved in this experiment were chosen for their differing manufacturing processes such as knitting or weaving; they were also chosen due to demonstrating different levels of volume resistivity. Volume resistivity of a polymer is a measurement of how well the plastic material negates the flow of current through a cubic volume of the material [17]. Nylon and generic polyester (PBT) have volume resistivities of $10^{14} - 10^{16}$ ohm-centimeter and 2.5×10^{16} ohm-centimeter respectively [18]-[20], which is several magnitudes of ten above 10×10^8 ohms-centimeter; the volume resistivity required to become recognized as an insulator. Ideal or data values acquired following the protocol insulating volume resistivity can be calculated by,

$$\rho_v = \frac{AR_v}{t} \quad (2)$$



Fig. 2. Photographs of the four integration textiles tested in our experiment. The number on the photo corresponds to which type of fabric it is within the numbered list on the next page.

[ASTM D257, IEC 60093] described in [20]. Where the A , R_v , and t in (2) stipulating the cross-sectional area of the material involved measured in centimeters-squared, the measured value for volume resistance in ohms, and average material thickness in centimeters respectively [21]. In order to find the relationship between the fabric properties and their impact on the sensing, we focus on a particular set of criteria. Criterion included: sensitivity, stability, linearity, durability, and pressure range of the sensor which will be defined below.

The four choices of fabric are pictured in Fig. 2 with labels on the next page. While nylon and polyester are both popular synthetic fibers, they have significantly dissimilar properties. Nylon is an elastic thermoplastic polymer fabric highly rated in its abrasion and weather resistant properties; classifying nylon as durable to nature. Nylon feels smoother to the touch than polyester, and as it is crafted from crude oil, it is resilient to oil and fuel. Some downsides to nylon are that it periodically produces and discharges static electricity that could short a circuit, is attacked by strong mineral acids due to remaining chemical group left after polymerization, and is made from crude oil and therefore not environmentally conscientious. This is a characteristic said to diminish once the material is mixed with around 20% conductive filaments and due to the very low volume conductivity [22]-[24]. Volume resistivity can ideally be calculated by,

$$\sigma_v = \frac{GL}{A} \quad (3)$$

Volumetric conductivity in Siemens per centimeter is calculated with the value for conductance G in ohms per cm,

$$G = \frac{A}{t\rho_v} \quad (4)$$

L the length through which the current must pass, and A the cross-sectional area. This was you can substitute the G and ρ_v values into the conductivity equation to get,

$$\sigma_v = \frac{At}{At\rho_v} \quad (5)$$

$$\sigma_v = \rho_v^{-1} \quad (6)$$

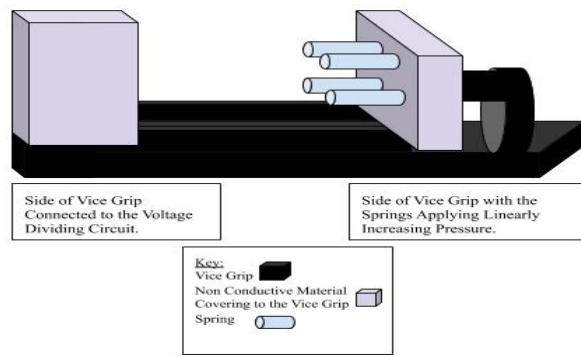


Fig. 3. An illustration of how the vice grip with springs looked.

Therefore, volume conductivity (3), is the inverse of volume resistivity (2). Causing the volume conductivity of nylon and polyester to equal between $10^{-14} - 10^{-15}$ and 4×10^{-17} Siemens per centimeter respectively in an idealized general situation. Polyester is categorized as a thermoplastic or thermoset material which means they both are resilient in high heat. Although, polyester is also known to be resistant to both stretch and shrink, which classifies it as dimensionally stable, which nylon is not. While Nylon does have a higher degree of abrasion resistance, polyester is a wrinkle resistant material. The wrinkling of nylon seems to make returning to its baseline more difficult, but this is merely an inference. The trends of consumer purchasing were originally highly invested in nylon, but as time has gone on polyester is one of the most highly purchased materials worldwide; this may be simply because people are fond of the softer feeling of polyester blended materials it is interesting that nylon manufacturers focus largely on electrical materials when - of these two - it is more prone to collect static electricity and randomly discharge [18],[22],[24].

Alongside the material composition, manufacturing techniques heavily influence the determination of functioning properties. Knitted fabrics are by design more: elastic, wrinkle resistant and permeable than woven. In addition, they exemplify better drape and resilience properties a useful characteristic for form-fitting applications. Comparatively, woven fabrics are typically superior in the categories of dimensional stability, salvaging, and strength of the material. Nevertheless, each of these fabric types is sufficient in acting as an insulating fabric on the basis of volume resistivity. The materials tested were,

- 1) 100% Nylon woven fabric in yellow
- 2) 92% Polyester 8% Nylon blend woven fabric in orange
- 3) 100% Polyester satin woven material in silver
- 4) 100% Polyester knit material in black

These are listed numbered in agreeance to the number on the photograph of the corresponding material in Fig. 2.

III. DATA ACQUISITION

A. Protocol

A Particle Photon board in conjunction with a voltage dividing circuit was powered by the USB Micro B port, which was set to supply a steady 3.3V out of the V_{IN} pin. We then connected this to the voltage dividing circuit comprised of five 10kiloOhm resistors from what is labeled as V_{IN} on Fig. 4. The Photon was sewn by non-conductive thread to a piece of fabric with embedded conductive trails that we could attach alligator clips to; this allowed for easy manipulation of the set-up for data collection in the future.

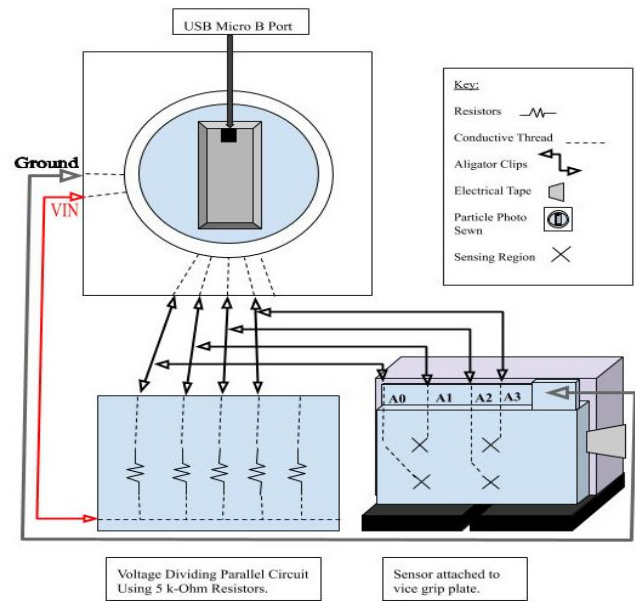


Fig. 4. An illustration of how the resistors, Photon, and vice grip were connected during data acquisition.

The Particle Photon board is set to collect the sensed values with a sampling rate of 67 Hz using 12-bit resolution. The data was streamed to a local computer for storage and later analyzed offline using MATLAB.

Each textile sensor was affixed upon one plate of a vice grip; while the opposing plate was affixed with four steel springs. The location of these springs was measured to to drive 197.4 Newtons/meter onto each sensing region. The vice grip begins at a maximum distance of 2.75 centimeters and minimizes to 1.75 centimeters. The vice grip in the same fashion relieves the pressure after reaching the minimum distance to return back to the starting distance. This set-up is visible at starting distance in Fig. 3.

B. Parameters

A scorecard was created to appropriately grade the qualities of the sensors isolating fabric, and the fabrics impact on pressure sensing applications to scale with our parameters. A scorecard was created to appropriately grade the qualities of the sensors isolating fabric, and the fabrics impact on pressure sensing applications. Also included in the testing apparatus was a Gold-Standard Force Resistive Sensor created by SparkFun with documentation in [25]. This sensor is a non-textile pressure sensor already on the market to allow for a standardizing factor. The scorecard uses a scale from 0 to 5 with each level requiring the sensor to meet a specified quality range for the given criteria. A score of a five was the highest-ranking classification. There were five criteria scored for a maximum of twenty-five points per sensor. We then gave each parameter a weight of 20% and calculated an average overall sensor score.

The parameters tested were defined as,

- 1) Sensitivity – defined as the minimum amount of change in the applied pressure to create a change in the output voltage. The range of each pressure sensor was adapted by finding voltage values for the maximum and minimum weight (N).
- 2) Stability – defined as the reliability across sensor readings such that the same voltage is measured for the same pressure applied every time.

- 3) Linearity – defined as the R score for a line fit to the sensors reading. Sensors' measured output should mimic the applied linear increase.
- 4) Durability – defined as the ability for the sensor to return to its original state after undergoing an applied pressure.
- 5) Pressure Range – defined as a measured ability to maintain linear relationship to pressure without undergoing saturation. This was realized by taking measurements before and after applying pressure and recording the differences. Denoted in table as just, "Range".

IV. RESULTS AND DISCUSSION

The results of the experiment confirmed that the integrating fabric layers do indeed have a significant impact on the sensing properties of the pressure sensor. There have also been some relations between the fabric properties and the sensors parameters found. As shown in Fig. 5, the reproducibility values vary significantly for each fabric, in fact they have a direct relation with fabric dimensional stability and elasticity. Less dimensionally stable and more elastic fabrics - like knitted polyester - show highest reproducibility.

The higher bulkiness of knit fabric as compared to weave leads to higher response uptake delay time; similarly, the elastic properties of Nylon lead to higher response uptake delay. At first the bulkiness and resistance to deformation dampens the applied pressure, while lowering the initial force to the piezoresistive layer. After the material is unable to hold against the force, the applied pressure reaches near the rest of the sensors. Poor dimensional stability of knit fabric combined with wrinkle resistant properties of polyester gives 100% polyester knit leads to excellent baseline delay.

No significant effect was seen on pressure range values matching the standard sensors, which signifies that the pressure range is a property of sensing layer and connecting circuit and not the integrating layer. Another side-effect of the compression resiliency of the knit fabric is a higher saturation value, which does not directly correlate to a higher range. It is also interesting to see that the pressure range of the standard SparkFun sensor was rated at a 2.3 on our grading scale; lower than all of the sensors fabricated sensors. Likewise, these e-Textile sensors almost all averaged higher than the sensor already on the market.

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Parameter Tested	Material Types Tested				
	100% Nylon Woven	92% Poly 8% Nylon	100% Poly Satin Woven	100% Poly Knit	SparkFun Sensor
Sensitivity	1.8	1.6	1.7	1.0	0.8
Stability	4.7	4.9	4.8	4.7	5.0
Linearity	4.7	4.9	4.8	4.7	4.9
Durability	2.8	4.9	5.0	4.9	3.3
Range	4.7	3.0	3.0	3.9	2.3
Average	3.7	3.0	4.0	3.9	3.2

Fig. 5. The outcomes of our experiment based on our defined parameters.

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